

INTERBAND CASCADE LASER PHOTON NOISE

Patrick A. Folkes
Army Research Laboratory
Adelphi, MD 20783-1197

ABSTRACT

We report measurements of the low-frequency photon noise and the relative intensity noise of an interband cascade laser as a function of laser current at 30 K and 100 K. Away from threshold, the laser primarily exhibits a frequency-independent photon noise spectral density in agreement with theory. At threshold, the observed photon noise spectral density exhibits large fluctuations at closely-spaced discrete frequencies. Thermal effects at 100 K result in a large increase in the photon noise above threshold.

1. INTRODUCTION

The interband cascade (IC) laser (Yang 1995; Meyer et al., 1996) is a relatively new type of semiconductor mid-infrared light source which is based on radiative transitions between the conduction and valence bands in type-II semiconductor quantum wells (QWs). Type-II unipolar IC lasers utilize the type-II band alignment in Sb-based QW structures and an applied potential to obtain a staircase-like bandstructure which enables each injected electron to cascade down a series of injection and active regions resulting in a quantum efficiency which is greater than one, which is the limit in interband diode lasers. Quantum cascade (QC) lasers (Faist et al., 1994) utilize a similar recycling of injected electrons to achieve lasing from stimulated intersubband transitions in a series of coupled quantum wells. Since the early experimental studies of the IC laser (Yang et al., 1997), improved material quality, device design and fabrication have led to significant improvements in IC laser performance (Bradshaw et al., 1999; Yang et al., 2002). Mid-infrared (IR) lasers are needed for commercial and military applications such as chemical sensing, IR countermeasures, free space communications and IR ladar. The spectral density of fluctuations in the output power of the IC laser, which is referred to as photon noise or laser intensity noise, is an important device performance parameter for these potential applications. However no theoretical or experimental investigation of the IC laser photon noise has been reported. In this paper we report constant-wave (cw) measurements of the IC laser photon noise and relative intensity noise as a function of current at 30 K and 100 K.

Comprehensive theoretical models (Rana and Ram, 2002; Gensty and Elsasser, 2005) of the photon noise in QC lasers have been developed. The theoretical model for the QC laser photon noise, which is based on a three level coupled QW active region, is quite general and its main features are qualitatively applicable to the IC laser. The QC laser noise theory is based on linearization of the coupled set of nonlinear rate equations to obtain rate equations for the fluctuations in electron and photon density. All gain sections in the IC laser are connected in series, as a result the electron density fluctuations in different gain stages are all coupled to the photon density fluctuations and the fluctuations in the current through the active regions. Current fluctuations are suppressed by electronic correlations and the small differential resistance of each gain stage compared with the total laser differential resistance. The theory assumes that, away from threshold, fluctuations can be modeled by small Langevin noise sources which results in a frequency-independent (white noise) photon noise spectral density for frequencies small compared to the laser modulation frequency. The theory is not applicable at threshold because the use of completely random Langevin noise sources and the linearization of the rate equations are not valid procedures at laser threshold (Lax, 1967). Above threshold, the contribution of nonradiative recombination processes to the QC laser photon noise is dominant and increases with bias current (Rana and Ram, 2002; Gensty and Elsasser, 2005). This is in contrast to interband diode lasers where spontaneous emission is the dominant noise source above threshold (McCumber, 1966).

2. EXPERIMENT

The IC laser structure has 18 active regions which are separated by an injection region composed of digitally graded InAs/Al_xIn_{1-x}Sb multi-QWs. The active region consists of coupled InAs, GaInSb and GaSb QWs separated by AlSb barriers. Under bias, electrons that are injected into the InAs QW, undergo radiative or nonradiative interband transitions into the GaInSb QW, tunnel into the adjacent GaSb QW and then enter the next injection region by interband tunneling. The laser structures were grown by molecular-beam-epitaxy and processed into mesa-stripe lasers with a mesa width of 15

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μm and a 1 mm cavity length. Both facets of the laser cavity were left uncoated. The lasers were mounted on a chip carrier which was affixed to the cold finger of a low temperature cryostat for measurement. The $3.45\ \mu\text{m}$ emission from one facet of our IC laser was focused onto a 1 mm diameter Judson InSb photodetector whose output is fed into an amplifier with a constant gain over the frequency range 0 – 203 KHz. Based on previous measurements of the laser's far-field pattern and our collection optics we estimate that 70% of the total output power from the facet is collected. The laser output power is proportional to the d.c. output of the amplifier. The low-frequency spectral density of the laser photon noise was measured by a Hewlett-Packard spectrum analyzer taking into account the thermal noise from the amplifier and the photodetector. Measurements of the photodetector current over the range of laser output power show that the photodetector current shot noise is negligible compared to the observed photon noise associated with fluctuations in the output power of the IC laser.

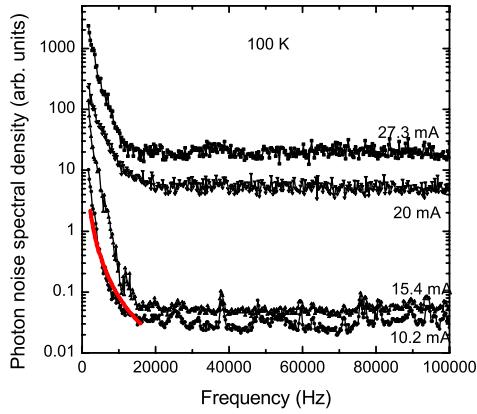


Fig. 1. Photon noise spectral density at 100 K for several cw laser currents. The thick solid line in the 10.2 mA plot is a $1/f^2$ fit to the data.

3. RESULTS

The measured photon noise spectral density over the frequency range 5 KHz – 100 KHz of a typical laser at 100 K and 30 K are shown in Fig. 1 and Fig. 2 respectively, for various cw laser currents. The spectrum analyzer's local oscillator signal appears over the range 0 – 5 KHz range. The laser threshold current I_{th} , is approximately 9.7 mA and 3.1 mA at 100 K and 30 K, respectively. For laser currents slightly above threshold the observed photon noise spectral density S_f , is

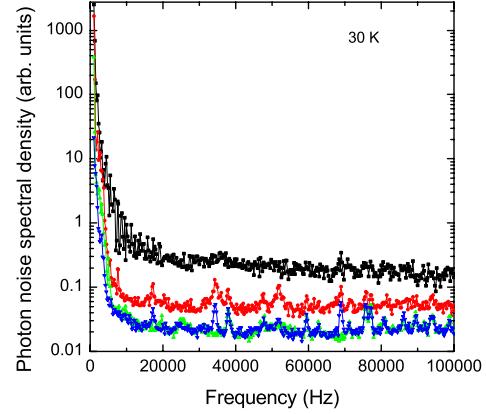


Fig. 2. Photon noise spectral density at 30 K for laser currents of 4.4 mA, 10.2 mA, 21.4 mA and 30.2 mA. Note that the 4.4 mA and the 10.2 mA plots nearly overlap.

predominantly constant for frequencies greater than around 16 KHz indicating that above threshold, the laser photon noise primarily has a white noise spectrum in agreement with theory (Rana and Ram, 2002; Gensty and Elsasser, 2005). At 30 K we observe a sharp decrease in the white noise component of S_f as the current I , is increased above threshold to 4.4 mA. The 30 K white noise is insensitive to I over the range $4.4\text{ mA} < I < 10.2\text{ mA}$ and then increases by roughly a factor of ten as I is increased from 10.2 mA to 30.2 mA. Theory (Rana and Ram, 2002) predicts the sharp decrease in S_f above threshold followed by a factor of 3.5 increase in S_f with increasing current over the range $2 < I/I_{\text{th}} < 10$. In contrast, the measured 100 K white noise component of S_f increases by a factor of around 600 when the laser current is increased from 10.2 mA to 27.3 mA. The observed large increase in the 100 K S_f with increasing current indicates that thermal effects result in a significant increase in the IC laser photon noise due to increased nonradiative recombination.

The photon noise spectral density has a low-frequency excess noise component which can be approximately fitted by a $1/f^2$ dependence over the 5 KHz – 16 KHz range as shown in Fig. 1 by the $1/f^2$ fit to the 10.2 mA excess photon noise over the range $3\text{ KHz} \leq f \leq 16\text{ KHz}$. The 30 K data shows that the excess noise component increases monotonically with current. At 100 K the ratio of the low-frequency excess noise at 5 KHz to the white noise increases from 25 db to 26 db as the laser current is increased from 10.2 mA to 15.4 mA and then decreases to

22 db as the current is increased to 27.3 mA. Fig. 3 shows that the 100 K photon noise spectral density changes to a $1/f^{1.6}$ frequency dependence over the range 5 KHz – 80 KHz when the current is increased from 27.3 mA to 37.9 mA. The mechanism for this change in the photon noise spectrum is unknown but clearly the change is induced by thermal effects. The observed temperature and current dependence of the low-frequency excess noise confirms that it is associated with photon fluctuations and not with low-frequency photodetector current fluctuations. The mechanism for the low-frequency excess photon noise could be similar to the deep-level trap mechanism responsible for generation-recombination noise in interband diode lasers (Hu et al., 2007).

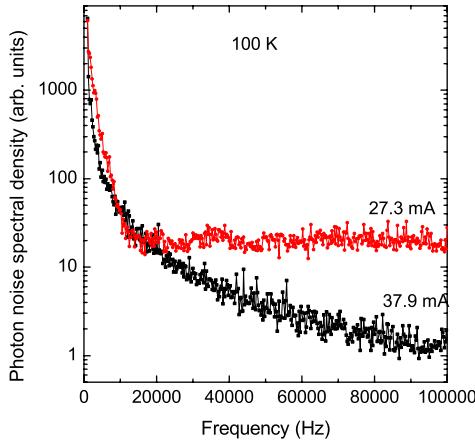


Fig. 3. Photon noise spectral density at 100 K for laser currents of 27.3 mA and 37.9 mA.

The laser relative intensity noise (RIN) is an important figure of merit which is given by the expression $RIN = 10\log(S_f/P^2)$, where S_f is the photon white noise spectral density and P is the laser output power. The average S_f over the range 20 KHz – 100 KHz is used to determine the RIN. The measured RIN at 30 K and 100 K is shown in Fig. 4 as a function of I/I_{th} . The measured RIN data takes into account the collection efficiency and the fact that light is collected from only one facet. At 30 K the measured RIN monotonically decreases from a value of -105 db at threshold to around -162 db for $I/I_{th} > 5$, in good qualitative agreement with the theoretical results (Rana and Ram, 2002) shown in Fig. 4. Over the range $1 \leq I/I_{th} \leq 3$ the measured 30 K RIN approximately shows a $1/P^2$ dependence in agreement with theoretical and experimental results [19,25]. Fig. 4 shows that at 100 K,

the measured RIN decreases from -112 db at threshold to -152 db at $I/I_{th} = 1.6$, and then increases to -134 db at $I/I_{th} = 2.9$. The observed increase in the RIN with increasing current over the range $1.6 < I/I_{th} < 3$ at 100 K, disagrees with theoretical prediction. The mechanism for the observed increase in the IC laser 100 K RIN is not known but the data clearly indicates that the increased cavity temperature induces an increase in photon fluctuations. For $1 < I/I_{th} < 2$, the observed IC laser RIN at 30 K and 100 K is about 15 db smaller than the QC laser RIN (Gensty et al., 2005). For $I/I_{th} > 4$, the 30 K IC laser RIN is comparable to the 88 K QC laser RIN, while the 100 K IC laser RIN is about 15 db higher than the 88 K QC laser RIN.

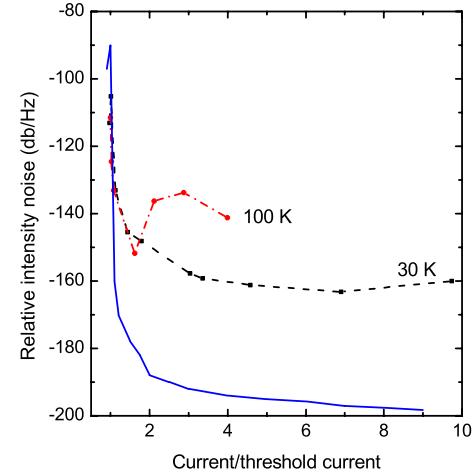


Fig. 4. Relative intensity noise (RIN) as a function of laser current at 30 K and 100 K. The solid line shows theoretical RIN (Rana and Ram, 2002).

At 30 K Fig. 5 shows that the laser exhibits a white noise spectrum just below threshold at $I = 3.0$ mA. At threshold, $I = 3.14$ mA, we observe striking large fluctuations at closely-spaced discrete frequencies in the photon noise spectral density as shown in Fig. 5. We observe the same striking changes in the 100 K photon noise spectral density as the current is increased from below threshold at $I = 9.5$ mA to $I = I_{th} = 9.73$ mA as shown in Fig. 6. Fig. 1 and Fig. 2 show that the large fluctuations in the photon noise spectral density are not observed above threshold. The 30 K photon noise spectral density at threshold closely resembles that observed at 100 K. The frequencies at which the large photon fluctuation peaks are observed at 30 K are identical to those observed at 100 K which suggests the possibility

that the large low-frequency photon fluctuations observed at threshold may be correlated.

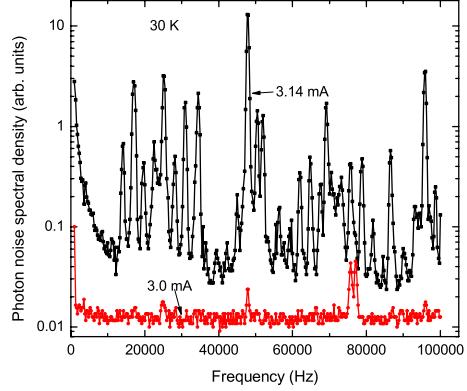


Fig. 5. Photon noise spectral density at 30 K just below threshold (3.0 mA) and at threshold (3.14 mA).

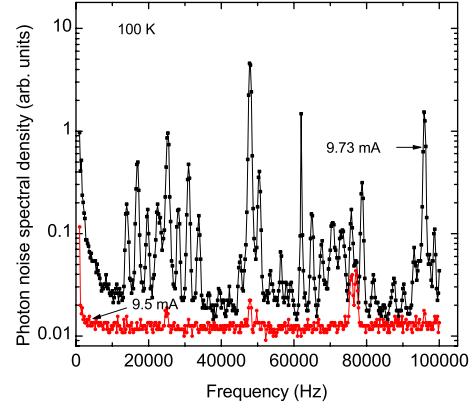


Fig. 6. Photon noise spectral density at 100 K just below threshold (9.5 mA) and at threshold (9.73 mA).

4. CONCLUSION

In conclusion, we report the first cw measurements of the low-frequency IC laser photon noise and relative intensity noise as a function of laser current at 30 K and 100 K. Just below and above threshold, the IC laser primarily exhibits a frequency-independent photon noise spectral density in agreement with theory. At threshold, the observed photon noise spectral density exhibits large fluctuations at closely-spaced discrete frequencies. At 30 K the dependence of the IC laser photon noise and the RIN on current qualitatively agrees with theory. Thermal effects at 100 K result in a much larger increase in the photon noise with increasing current than theoretically predicted and significant disagreement between the observed and theoretical dependence of the RIN on current. Further studies are needed to understand the observed thermal effects on IC laser photon noise, photon fluctuations at threshold and the excess low-frequency photon noise.

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